

Detection of Leptonic Dark Matter

E. A. Baltz^{1,2} and L. Bergström^{1,3}

¹*Kaiv Institute for Theoretical Physics, University of California at Santa Barbara, Santa Barbara, CA 93106-4030*

²*Permanent address: ISCAP, Columbia Astrophysics Laboratory, 550 W 120th St.,*

Mail Code 5247, New York, NY 10027 eabaltz@physics.columbia.edu

³*Permanent address: Department of Physics, Stockholm University,*

AlbaNova University Center, S-106 91 Stockholm, Sweden lb@phys.to.se

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Weakly interacting massive particles (WIMPs) are among the favored candidates for cold dark matter in the universe. The phenomenology of supersymmetric WIMPs has been quite developed during recent years. However, there are other possibilities which have not been discussed as much. One example is a right-handed massive neutrino, which has recently been proposed in the context of a version of the Zee model for massive neutrinos. This TeV-scale, leptonic WIMP (or LIMP, for short) may at first sight appear to be essentially undetectable. However, we point out that the radiatively induced annihilation rate into leptons and photons is bound to be substantial, and provides a conspicuous gamma-ray signature for annihilations in the galactic halo. This gives a window of opportunity for Air Čerenkov Telescopes with ability to observe the galactic center, such as the HESS and CANGAROO arrays, and also for the GLAST space telescope. In addition, the contribution to the positron cosmic ray flux is in principle detectable, but this would require very strong local density enhancements in the dark matter halo distribution.

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I. INTRODUCTION

Recently, Krauss, Nasri and Trodden ([1], KNT in the following) proposed an interesting model, where a right-handed neutrino of mass on the order of a few TeV plays a crucial role in giving mass to the otherwise massless standard model neutrinos through a high-order loop mechanism. This is a version of the Zee model [2], which has been quite successful in reproducing the observed mass and mixing pattern of solar and atmospheric neutrinos (see, e.g., [3]). The particle content of the Zee model is given by two Higgs doublets Φ_1 and Φ_2 , and a charged field S which transforms as a singlet under $SU(2)$, with Lagrangian

$$\mathcal{L}_{Zee} = f_{\alpha\beta} L_\alpha^T C i \tau_2 L_\beta S^+ + \mu \Phi_1^T i \tau_2 \Phi_2 S^- + \text{h.c.} \quad (1)$$

KNT consider a variant where neutrino masses appear only at the three loop level. To achieve this they supplement the SM fields with two charged singlet scalars S_1 and S_2 and one right handed neutrino N_R . Lepton number is broken explicitly by including a Majorana mass term for the right-handed neutrino, and imposing a discrete Z_2 symmetry under which the SM fields and S_1 are singlets but S_2 and N_R transform as

$$Z_2 : \{S_2, N_R\} \longrightarrow \{-S_2, -N_R\}, \quad (2)$$

forbidding Dirac masses for the neutrinos. This gives the Lagrangian

$$\begin{aligned} \mathcal{L}_{\text{KNT}} = & f_{\alpha\beta} L_\alpha^T C i \tau_2 L_\beta S_1^+ + g_\alpha N_R S_2^+ l_{\alpha R} \\ & + M_R N_R^T C N_R + V(S_1, S_2) + \text{h.c.}, \end{aligned} \quad (3)$$

in which the potential $V(S_1, S_2)$ contains a $(S_1 S_2^*)^2$ coupling. It is assumed a mild hierarchy of masses $M_R < M_{S_1} < M_{S_2} \sim \text{TeV}$ and that the Yukawa couplings $f_{\alpha\beta}$, g_α are of order unity, making N_R stable in view of the discrete symmetry. Left-handed Majorana neutrino masses are induced at three-loop order. For $M_{S_2} \sim \text{TeV}$, KNT find an effective dimension-five effective mass scale of $\Lambda > 10^9 \text{ GeV}$, giving neutrino masses at the 0.1 eV scale without involving fundamental mass scales significantly larger than a TeV.

II. TWO-BODY TREE-LEVEL ANNIHILATION RATES

The discrete symmetry and the fact that N_R is lighter than the charged scalars means that N_R becomes stable and therefore a natural dark matter candidate. Through S_2 exchange it coupled to charged leptons in the early universe strongly enough to give the correct relic density, but extremely weakly today. Current direct dark matter detectors employ scattering on nucleons, and will not be sensitive to the available leptonic interactions. One could imagine techniques based on atom level transitions [4], but a simple estimate shows that the rate is typically less than one event per ton per year, thus several tons of active detector material would be needed – a very difficult task given that a gaseous phase detector will probably be necessary.

Similarly, indirect detection through neutrinos from the Earth or the Sun will not be possible, since the cross section for capture is negligibly small.

We therefore turn to indirect detection through annihilation in the galactic dark matter halo. First, it may be useful to review the thermal production mechanism in the early universe. Since the N_R is a Majorana particle, its annihilation into a lepton pair shows the usual helicity suppression $\sigma v \propto m_\ell^2$ for the S-wave. Repeating the original calculation of Goldberg for photinos [5], the cross section can be written

$$\sigma v (N_R N_R \rightarrow \ell^+ \ell^-) = \frac{g_\ell^4}{8\pi m_N^4 (1+f^2)^2} \left[m_\ell^2 + \frac{2}{3} \left(\frac{1+f^4}{(1+f^2)^2} \right) m_N^2 v^2 + \dots \right], \quad (4)$$

where m_ℓ is the charged lepton mass, $m_S = f m_N$ the S_2 mass and m_N the LIMP (N_R) mass. Note that for f not too much larger than unity, the factor in square brackets is typically close to 0.5. This means that for m_N in the TeV range, the P-wave cross section (the term proportional to v^2 in Eq. (4)) will determine the freeze-out temperature T_f and therefore the relic abundance [1]. As usual for a WIMP, one finds $T_f/m_N \sim 1/20$, and so $\langle v^2 \rangle_f = 6T_f/m_N \sim 0.3$. The requirement that the LIMP be the dark matter particle, with relic abundance $\Omega_N h^2 \approx 0.1$, as indicated from a joint analysis of cosmic microwave background and large scale structure data (see, e.g., [6]), then fixes the cross section at freeze-out to be [7, 8]

$$\sum_{\ell=e,\mu,\tau} \langle \sigma v \rangle_f \approx \frac{\sum_\ell g_\ell^4}{80\pi m_N^2 (1+f^2)^2} \approx 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}. \quad (5)$$

For a given N_R of mass m_N , this fixes the normalization of the combination $\sum_\ell g_\ell^4/m_N^4(1+f^2)^2$ which appears in many annihilation formulas. We can then estimate the total annihilation rate into lepton pairs $\ell^+ \ell^-$ at rest (i.e. in S-wave) putting $v = 0$ in Eq. (4). We find

$$\sigma v (N_R N_R \rightarrow \ell^+ \ell^-)_{v \sim 0} \approx 3 \times 10^{-25} \left(\frac{g_\ell^4 m_\ell^2}{\sum_\ell g_\ell^4 m_N^2} \right) \text{ cm}^3 \text{ s}^{-1} = 10^{-25} \left(\frac{m_\ell^2}{m_N^2} \right) \text{ cm}^3 \text{ s}^{-1} \text{ (flavor universal)}. \quad (6)$$

In the remainder of this paper we will assume flavor universality, namely $g_e = g_\mu = g_\tau = g$. For a TeV LIMP, this looks like a phenomenally small annihilation rate for the e^+e^- and $\mu^+\mu^-$ channels. Even for $\tau^+\tau^-$, the helicity suppression is of the order of 10^{-6} (at that level, the P-wave term in the galactic halo starts to contribute since typical galactic velocities correspond to $v \sim 10^{-3}$). One would therefore be tempted to conclude that the LIMP, despite being a good dark matter candidate, has little chance to be detected in any direct or indirect detection experiment. We note that in order that the couplings g_ℓ not be much larger than unity, for nearly degenerate N_R and S_2 , m_N cannot be too much heavier than 1 TeV, but could be significantly lighter.

III. THE DETECTABILITY OF N_R THROUGH GAMMA-RAYS

The small annihilation rate, unlike the small scattering rate (which is caused by the leptonic nature of the candidate), is due to the Majorana nature of N_R which implies the absence of large S-wave two-body annihilation at tree level [5]. Any higher order process which does not have this helicity suppression will have a chance to dominate the annihilation rate completely. This is precisely the kind of interesting situation investigated many years ago for the case of a pure photino coupling through light selectrons to electrons, positrons and photons [9]. (That particular candidate is now less plausible in view of results from the LEP accelerator.) In particular, we can immediately take over the results of [9] to write the differential cross section for the radiative, non-helicity suppressed process $N_R N_R \rightarrow \ell^+ \ell^- \gamma$ as (here the annihilation rate $\Gamma = \sigma v/2$)

$$\frac{d\Gamma}{dE_\gamma dE_\ell} (N_R N_R \rightarrow \ell^+ \ell^- \gamma) = 3 \times 10^{-25} \frac{g_\ell^4}{\sum_\ell g_\ell^4} \frac{\alpha(m_N^2 + m_S^2)^2}{\pi m_N} F(E_\gamma, E_\ell) \text{ cm}^3 \text{ s}^{-1} \text{ GeV}^{-2}, \quad (7)$$

where we have neglected the lepton masses (a good approximation also for the τ^\pm for TeV LIMPs), and where

$$F(E_\gamma, E_\ell) = \frac{(m_N - E_\gamma)(2m_N^2 - 4m_N E_\ell - 2m_N E_\gamma + 2E_\ell^2 + 2E_\ell E_\gamma + E_\gamma^2)}{(3m_N^2 - 2m_N E_\ell - 2m_N E_\gamma + m_S^2)^2 (m_N^2 - 2m_N E_\ell - m_S^2)^2}. \quad (8)$$

Note that the total rate for gamma rays of this process is fixed by the cross section giving the relic density - it is independent of the values of the individual g_ℓ in this massless limit. The strength of this process is seen to be of the order of α/π times the annihilation rate at freeze-out, which is orders of magnitude larger than the helicity-suppressed two-body S-wave annihilation rate. This will mean, as we shall see, that there is a hope of detecting the LIMP in gamma-rays, and perhaps also in an anomalous positron component of the cosmic rays. On the other hand, since all three charged SM leptons are too light to decay into baryons, indirect detection through antiprotons (or antideutrons) is not expected for the LIMP. A nice feature of the result (Eq. 7) is its model independence. For any dark matter candidate of this type (a Majorana particle coupling mainly to leptons through charged scalar exchange) we expect this strength of the radiative annihilation signal. This is to be contrasted with the situation in the MSSM, where the predicted gamma-ray signal for a SUSY WIMP of any given mass depends strongly on a large number of additional supersymmetric parameters. However, there are astrophysical uncertainties which make the expected absolute fluxes difficult to estimate despite this robustness of the particle physics properties.

By integrating Eq. 7 over E_ℓ (with lower and upper integration limits $m_N - E_\gamma$ and m_N , respectively) we get the differential photon spectrum. Similarly, by integrating over E_γ between $m_N - E_\ell$ and m_N the differential lepton spectrum (and the identical anti-lepton spectrum) is obtained. Apart from the overall normalization, which is fixed by the relic density and contains a factor $(m_N/m_S)^4$ strongly favoring a scenario with at most a mild hierarchy of these masses, the shapes of these distributions depend only on the scaled energies E/m_N and the ratio m_N/m_S .

Since all leptons can be treated as massless, the distributions are identical for $e^\pm\gamma$, $\mu^\pm\gamma$ and $\tau^\pm\gamma$, so from the point of view of this gamma-ray signature, it is of no importance whether the N_R couples universally to leptons or not. There are in principle a significant number of hard photons in the tau decay chain from pion decays, but we have checked that the direct photons from $\ell^\pm\gamma$ strongly dominate in all cases we illustrate. For, e.g., the positron signal there may be differences, since muons and taus give positrons with softer spectra in their decays, as discussed in the next Section. In Fig. 1 (a) and (b) we show examples of these distributions for $m_N/m_S = 0.8$ and 0.2, plotted on logarithmic and linear scales, respectively. As can be seen, both the gamma and the lepton spectra are exceptionally hard, peaking near the maximum energy (which in both cases is equal to m_N). This is optimal from the point of view of detection, as most conceivable sources of background tend to give soft spectra, rapidly falling with energy.

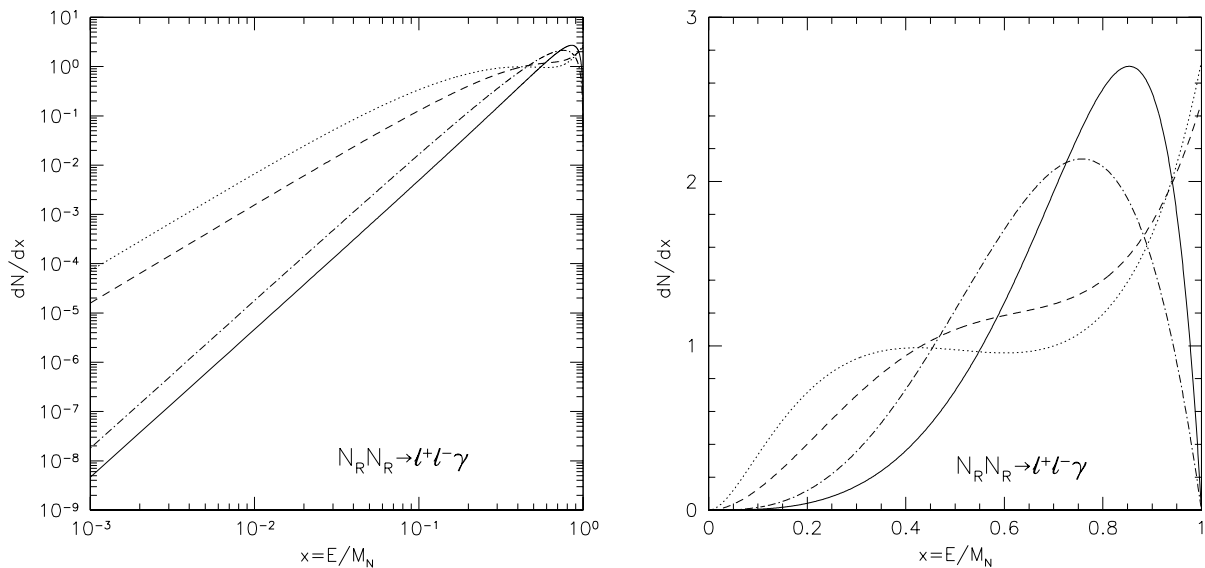


FIG. 1: (a) The differential photon spectrum for the process $N_R N_R \rightarrow \ell^+ \ell^- \gamma$, normalized to unity, for $m_N/m_S = 0.8$ (solid line) and $m_N/m_S = 0.2$ (dash-dotted line), as well as the lepton (or the identical anti-lepton) spectrum for the same mass ratios (dotted line and dashed line, respectively). (b) Same as in (a) but plotted using a linear scale on both axes.

The obvious place to search for the gamma-ray signal is in the direction of the galactic center, where the dark matter distribution is expected to be strongly enhanced. N-body simulations indicate that cold dark matter, of which

the LIMP is an example, is even likely to form a density cusp $\rho(r) \sim 1/r$ near the center (the so-called Navarro-Frenk-White or NFW profile [10]). The observational situation concerning rotation curves and the distribution of dark matter in spiral galaxies, including our own, is however far from clear at the moment, and the same is true for the N-body calculations where different groups still seem get different results [11, 12]. Even more unclear is the interesting possibility of the massive black hole transforming the cusp into a very sharp spike with dramatically enhanced density [13, 14, 15].

The best we can do at the moment is to assume an NFW profile, keeping in mind that the predicted rates can be either much lower (in the case of the absence of both a cusp and a spike) or much higher (in the case of a steeper cusp, as some N-body simulations indicate, or a spike, or a clumpy halo [16] as also indicated by simulations [17]). Here we note the importance of the clumpiness of the halo: since the annihilation rate is proportional to the square of the density ρ , it is enhanced over the prediction for a smooth halo by a clumpiness parameter $C = \langle \rho^2 \rangle / \langle \rho \rangle^2 \geq 1$.

The rate of gamma-rays from a given halo profile has been elaborated in [18]. Combining the results of that work with those given here, we predict a gamma-ray flux from the galactic center (treated as a point source, so the units are in $\text{cm}^{-2} \text{s}^{-1} \text{GeV}^{-1}$)

$$\frac{d\Phi_\gamma}{dE_\gamma} = 1.3 \times 10^{-11} \left(\frac{1 \text{ TeV}}{m_N} \right)^2 \left(\frac{\langle J \rangle_{\Delta\Omega} \Delta\Omega}{100} \right) \frac{(m_N^2 + m_S^2)^2}{m_N} \int_{m_N - E_\gamma}^{m_N} dE_\ell F(E_\gamma, E_\ell), \quad (9)$$

where the line-of-sight integral J is defined in [18], and $\langle J \rangle_{\Delta\Omega}$ is the average of this line-of-sight integral over the acceptance $\Delta\Omega$ of a gamma-ray telescope; for a NFW profile, the maximal value of the product $\langle J \rangle_{\Delta\Omega} \Delta\Omega \sim 100$ for $\Delta\Omega \sim 10^{-3}$ [18] (similar, or larger, values would be obtained for the Moore profile [19] $\rho(r) \sim 1/r^{1.5}$). The background is difficult to estimate (in fact, much of the presently perceived diffuse “background” may turn out to be part of the kind of signal discussed here). For the sake of the argument, we will take the simple estimate given in [18], extrapolated from the flux measured by EGRET towards the galactic center:

$$\left(\frac{d\Phi_\gamma^{bkg}}{dE_\gamma d\Omega} \right)_{g.c.} = 4.8 \times 10^{-13} \left(\frac{1 \text{ TeV}}{E_\gamma} \right)^{2.7} \text{ cm}^{-2} \text{s}^{-1} \text{GeV}^{-1} \text{sr}^{-1}. \quad (10)$$

An inevitable consequence of the LIMP coupling to a charged scalar is that the loop-induced process $N_R N_R \rightarrow \gamma\gamma$ should also occur [9], with cross section

$$\sigma v (N_R N_R \rightarrow \gamma\gamma) \approx \frac{(\sum_\ell g_\ell^2)^2}{\sum_\ell g_\ell^4} \times 4 \times 10^{-30} \text{ cm}^3 \text{s}^{-1}. \quad (11)$$

Note that since all leptons contribute coherently to the loop amplitude, the rate is more favorable for a universal lepton coupling. In the case $g_e = g_\mu = g_\tau = g$, the value for σv becomes $1.2 \times 10^{-29} \text{ cm}^3 \text{s}^{-1}$ which is quite sizable. Note that this result is independent of the N_R and S_2 masses [9]. (One may also note that since S_2 is an SU(2) singlet, there is no corresponding $Z\gamma$ final state.)

The line flux then becomes

$$\Phi_{\gamma\gamma}^{g.c.}(E_\gamma = m_N) \approx 1.2 \times 10^{-13} \left(\frac{1 \text{ TeV}}{m_N} \right)^2 \text{ cm}^{-2} \text{s}^{-1}. \quad (12)$$

This would appear as a sharp spike (with relative width of the order of the Doppler broadening due to LIMP motion, i.e. of the order of 10^{-3}), in an instrument with perfect energy resolution. However, ACTs have an energy resolution of the order of 5 – 10% at best. If we assume 5%, the gamma spike for a TeV LIMP spreads out over 50 GeV, a differential rate near a TeV similar to the radiative processes discussed above.

For smaller LIMP masses of the order of 100 GeV, one gets into the mass range where the GLAST gamma-ray telescope [20] will be operative (it will detect gamma-rays up to 300 GeV). The energy resolution for GLAST will depend on the angle of incidence and may reach a few percent, making it possible for the line to stand out against background. The detection of such a line would eliminate all possible confusion with plausible astrophysical backgrounds.

In Fig. 2 (a) we show the flux predicted from Eq. (9) and Eq. (12) together with the background estimate Eq. (10) for a 100 GeV LIMP, and 110 GeV S_2 , NFW profile and $\Delta\Omega = 10^{-3}$. For this energy range, we have used an energy resolution of 3%. It may be difficult to push the N_R mass much below 100 GeV without fine tuning the parameters of the KNT model (and the S_2 mass is also bounded by LEP results to be larger than around 100 GeV). We note that with the S_2 (and thus S_1) only 10% higher in mass than the N_R , a careful analysis should really take coannihilations with S_2 into account when estimating the relic density, and thereby fixing the interaction strength. In analogy to

SUSY models where R-parity stabilizes the lightest superpartner, in this model the Z_2 symmetry stabilizes the lightest odd state; a complete calculation would include all odd states, in this case N_R and S_2 . However, coannihilations are unlikely to change the relic density by more than a factor of a few, a small correction compared with the very large astrophysical uncertainties related to the radial distribution of dark matter near the galactic center.

The natural mass range for the LIMP is around 1 TeV, where GLAST runs out of sensitivity but where ground-based arrays of Air Čerenkov Telescopes with large collecting area can detect a signal. Indeed, there are already such arrays of telescopes planned or in operation such as CANGAROO [21], HESS [22], VERITAS [23] and MAGIC [24]. In particular, CANGAROO and HESS are well located to observe the galactic center for a sizable fraction of their observing time. As can be seen from the figure, the signal with these assumptions would stand out from the gamma-ray background. (We do not enter here into the more technical issue of rejecting other types of background, such as from hadrons and electrons, where there is a steady improvement in the techniques employed.)

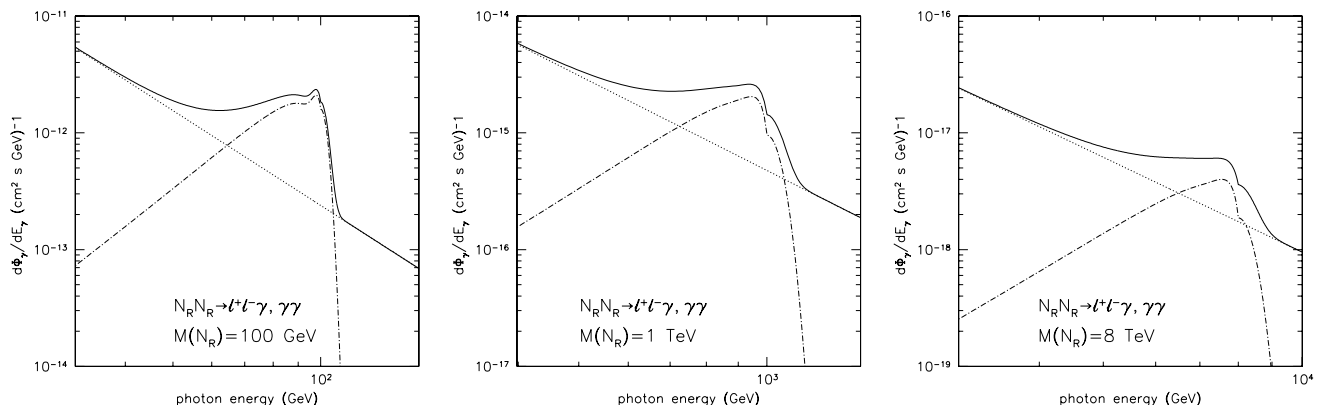


FIG. 2: (a) The total gamma-ray flux expected from a $\Delta\Omega = 10^{-3}$ sr cone around the galactic center (solid line). The flux is composed by a power-law background extrapolated from EGRET data (dotted line) and a 100 GeV LIMP annihilating with a cusped (NFW) density profile through a 110 GeV scalar S_2 , giving both a continuous spectrum and a 2γ line. An energy resolution of 3% has been assumed for the line signal. (b) Same as (a) for a 1 TeV LIMP, $m_{S_2} = 1.1$ TeV. Here the line has been smeared by an assumed energy resolution of 5%. (c) Same as (b) for an 8 TeV LIMP, $m_{S_2} = 8.8$ TeV.

In Fig. 2 (b) and (c), the curves are shown for a LIMP of mass $m_N = 1$ TeV, $m_{S_2} = 1.1$ TeV, and $m_N = 8$ TeV, $m_{S_2} = 8.8$ TeV, respectively. These should be clearly observable with a very conspicuous “bump” in the spectrum, for the halo parameters chosen. We note with interest that preliminary results from the CANGAROO collaboration indeed show an excess flux of TeV gamma-rays from the galactic center [25]. The absolute flux level for this possible signal seems higher than that predicted in Eq. (9), so an enhancement beyond that provided by the NFW profile would then be indicated.

An interesting question is what would happen to the leptons. To be specific, assume that there is lepton universality in the N_R couplings. Then there will be equal amounts (apart from very small lepton mass corrections) of τ^\pm , μ^\pm and e^\pm leptons. The produced τ^\pm and μ^\pm will decay into lower-energy electrons and positrons (see next Section), and the primary high-energy electrons and positrons will quickly radiate due to synchrotron and inverse Compton processes. In fact, an analysis by Bertone, Sigl and Silk [26] points to the existence of a radio signal that may be caused by just the kind of TeV-scale dark matter particles discussed here, if the magnetic field near the galactic center is strong enough. In any case, this would be a signal to search for, were a TeV gamma-ray excess to be confirmed.

IV. PREDICTIONS FOR COSMIC-RAY POSITRONS

In the previous section the annihilation process $N_R N_R \rightarrow \ell^+ \ell^- \gamma$ was discussed with the idea of detecting the high energy photons produced. We can also make a prediction for the cosmic ray positron flux from this process. As shown below, the positron flux is quite low, and not likely to be detectable unless the clumpiness factor of the galactic halo is quite large.

Positrons might come from any of the three leptonic channels. In the direct process $N_R N_R \rightarrow e^+ e^- \gamma$ the positrons are quite energetic. The energy is downgraded somewhat in the muon channel, since some of the energy goes to neutrinos: $N_R N_R \rightarrow \mu^+ \mu^- \gamma \rightarrow e^+ e^- \nu_e \bar{\nu}_e \nu_\mu \bar{\nu}_\mu \gamma$. The spectrum is softest for the tau channel $N_R N_R \rightarrow \tau^+ \tau^- \gamma$, since

there are many hadronic modes with longer decay chains yielding positrons (and electrons) in the end. We also include the simpler processes $N_R N_R \rightarrow \ell^+ \ell^-$. For electrons this is negligible unless M_N is very small and $M_S \gg M_N$ is much larger. However, for muons and especially taus, the simple process can be important as the helicity suppression is less severe. All of this can be accounted for with standard tools; in particular we have used results from the PYTHIA event generator [27] as tabulated in DarkSUSY [28] for the positron spectra from the muon and tau decay chains. Folding in the annihilation cross section, we can then compute the volume production rate of positrons in the Galactic halo ($d\Gamma/dE$) in units of $\text{cm}^3 \text{s}^{-1} \text{GeV}^{-1}$.

The propagation of positrons in the Galactic environment is complex. The gyroradii of charged particles in the tangled magnetic fields are quite small, and the motions can be modeled as a diffusion process. Furthermore, positrons lose energy rapidly to both synchrotron radiation, and in addition to inverse Compton scattering with the cosmic microwave background and with diffuse starlight. We use the propagation model in Ref. [29] to calculate the observed flux at the Earth. The model includes diffusion in an infinite slab, a reasonable approximation given the fact that detectable positrons are produced within a few kpc, thus an outer radial boundary is unimportant. The energy losses to synchrotron and inverse Compton processes are included. This model is in rough agreement with earlier work [30], though the inclusion of inverse Compton scattering from starlight doubles the energy loss rate. More sophisticated models give similar results [31]. We note here that the question of the halo profile is much less important in calculating the positron flux, as their effective range is only a few kpc. Thus, it is the less uncertain local dark matter density that is important for the positron flux.

The HEAT collaboration has in fact reported an excess of positrons above about 10 GeV in the cosmic ray positron fraction $f = e^+/(e^+ + e^-)$ [32], later confirmed in a different instrument by HEAT-pbar [33]. We now discuss the possibility that this excess might be due to annihilating LIMPs. The fluxes of positrons are typically too small by a factor of 10^4 if a smooth halo is assumed. This might seem hopeless, but the clumpiness parameter could be this large, boosting the signal accordingly. In order to produce an excess at 10 GeV, lighter LIMPs are preferred. Assuming that the LIMP must be heavier than 100 GeV to escape discovery (actually, it is the heavier charged scalars S_1 and S_2 which would be seen at e.g. LEP), we illustrate some LIMP models that give an acceptable positron flux to explain the HEAT results in Fig. 3 (albeit with the very large clumpiness parameter). Other explanations for this excess have been put forward elsewhere [29, 34, 35]. In the second panel of Fig. 3 we show some LIMP models with larger masses that do not do well in explaining the current excess. However, future experiments such as AMS [37] and PAMELA [38] may be able to probe such models with higher accuracy, and we estimate that boost factors a factor of five or ten smaller (of order 10^3) would still produce an interesting signal for such experiments.

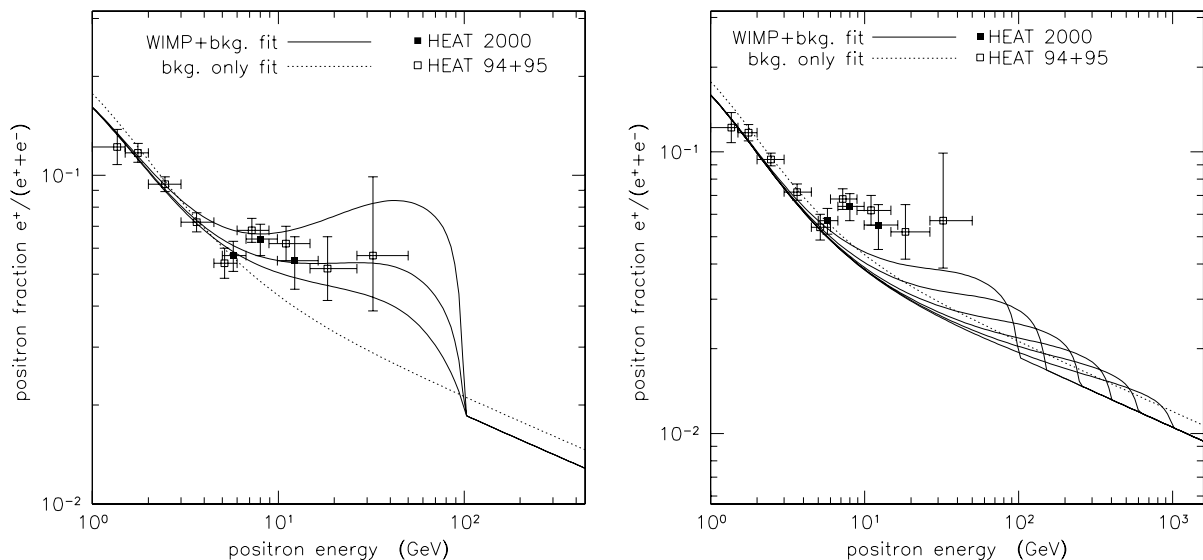


FIG. 3: Cosmic ray positron fraction for LIMP models. The data from the two HEAT experiments is illustrated, along with the expected value (dotted line). (a) Variation of M_S with values of (top to bottom) 120, 150, and 200 GeV, with M_N fixed at 100 GeV. The boost factor is fixed at 2×10^4 . (b) Variation in M_N , with values of 100, 150, 250, 400, 600, and 1000 GeV. In all cases $M_S = 1.2M_N$. Here a boost factor of 4×10^3 is used.

V. DISCUSSION AND CONCLUSIONS

We have discussed the possibility of astrophysically detecting a right-handed neutrino cold dark matter candidate arising in a recently proposed modified Zee model. As the interactions are only leptonic, current elastic scattering experiments are not sensitive to this particle. Annihilations in the galactic halo, with both two and three body final states, may provide detectable numbers of high energy photons or positrons, though these predictions rely heavily on the structure of the Galactic halo, both in core profile and in spectrum of substructure.

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